Methods for efficient modelling of progressive failure in laminated fibre-reinforced composites

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2019

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOLID AND STRUCTURAL MECHANICS

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ISBN 978-91-7905-233-1

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr. 4700
ISSN 0346-718X
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SE-412 96 Göteborg
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Cover:
Illustration of one of the carbon fibre reinforcements (uni-weave non-crimp fabric, style 4510 from Porcher Industries) used for validation testing in the research project.

Chalmers Reproservice
Göteborg, Sweden 2019

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Abstract

To meet increasing demands on reduced CO_2 emissions, the automotive industry is currently very active in research to reduce vehicle weight by incorporating laminated composites (primarily carbon fibre-reinforced polymers) into structural components.

Historically, composite materials have mainly been used in the aerospace industry, whereby CAE-based design and development tools for composite structures have been developed primarily to the specific needs and requirements in this industry. In general, the crashworthiness of aerospace structures is only assessed to a small extent compared to that of automotive structures. Consequently, no suitable numerical simulation tools, capable of assessing the crashworthiness of composite automotive structures, have been developed.

The fracture process of laminated composites is more complicated than that of metals, the dominant class of materials used in automotive crash protection systems today. Thus, numerical models developed for metals cannot be used to accurately predict the crashworthiness of composite structures. Instead, high-fidelity models that can resolve the complicated fracture process must be used. However, these models require excessive computational times, making industrial crash simulations infeasible. It is therefore crucial to develop computationally efficient numerical tools, which are able to accurately predict the crashworthiness performance of composite structures.

In this thesis, I will present a route towards full-scale vehicle crash simulations using a computationally efficient adaptive method. The method is based on an equivalent single-layer shell model which, during the analysis, is adaptively transformed to a high-fidelity model in areas where higher accuracy is required. This way, the increased computational cost, associated with the analysis of progressive damage in laminated composites, can be limited both in time and to the pertinent areas of the model.

The adaptive modelling method can successfully reproduce the same level of accuracy as a high-fidelity model, at lower computational cost. Consequently, this method can help to enable computationally efficient crash simulations of laminated structures, which in the long run will allow composite materials to have a widespread use in future automotive vehicles.

Keywords: Composites, Progressive failure, Crash simulation, Adaptive modelling

to Anna, Nila and Rio

Preface

After finishing my Master's degree at Chalmers, I was eager to get to work as a CAE-engineer. This, despite knowing that my thirst for knowledge and perfectionist personality probably would be better of in academia. Two years in, I (by chance) attended a meeting where the idea for a research project was discussed. The project combined my interest for crash simulations and composite materials. Well, not being ready to go back to school, I merely watched the process to get funding from the outside. However, this process took some time. So long that I had time to realise that I needed to be one of the intended PhD students performing the research.

I am glad that I was accepted to be a part (and allowed to take a leave of absence from my employer ÅF) of these research projects called *Modelling crash behaviour in future lightweight composite vehicles — Step 1 and 2.* They are funded by the Swedish Strategic Vehicle Research and Innovation Programme on Vehicle and Traffic Safety (Grant No. 2012-03673 and 2016-04239) and co-funded by the industrial partners, which is gratefully acknowledged. The work has been carried out between October 2013 and December 2019[1] at the Division of Material and Computational Mechanics at Chalmers University of Technology.

I would like to thank my supervisor Associate Professor Martin Fagerström, co-supervisor Dr Jim Brouzoulis and examiner Professor Ragnar Larsson for their support and guidance on my path through the academic jungle. Further thanks to Dr. Jesper Karlsson at DYNAmore Nordic and all the other the persons involved (you know who you are) in the research projects. Also all the colleagues at both Chalmers and and RISE (SICOMP) deserve a great thanks. My work would have been impossible without the assistance and support of the people I have the pleasure of working with. I will in the thesis at several places refer to 'we', to acknowledge that I have not done this work all by myself. Finally, I want to thank all my family members and express my love to Anna (the wife), Nila (the son) and Rio (the dog) for supporting me in this endurance.

Now, almost ten years after finishing university for the first time, I'm once again ready to finish studying. But, I guess, we'll see what happens. Ask me again in ten years...

Göteborg, December 2019
Johannes Främby

[1] Yes, it takes over six years when you decide to have a 'Lic baby' in the middle of it.

Abbreviations

Extended Summary

AFEM	Augmented Finite Element Method
BBA	Building Block Approach
CAE	Computer Aided Engineering
CFRP	Carbon Fibre-Reinforced Polymer
CZ	Cohesive Zone
DOF	Degrees Of Freedom
ESL	Equivalent Single-Layer
FE	Finite Element
FRP	Fibre-Reinforced Polymer
IP	Integration Points
LW	LayerWise
MCID	Matrix-Crack Induced Delamination
SEA	Specific Energy Absorption
UD	Unidirectional
WP	Work Package
XFEM	eXtended Finite Element Method

Paper A

ESLM	Equivalent Single-Layer Models
DoF	Degrees of Freedom
FE	Finite Element
FRP	Fibre-Reinforced Polymer
FSDT	First-Order Deformation Theory
LSF	linear Least Square Fit
LWM	LayerWise Models
PCB	Periodic Boundary Condition
RMVT	Reissner Mixed Variational Theorem
RVE	Representative Volume Element
XFEM	eXtended Finite Element Method

Paper B

CZM	Cohesive Zone Models
DCB	Double Cantilever Beam
ENF	End Notch Flexure
ESL	Equivalent Single-Layer
FE	Finite Element
FRP	Fibre-Reinforced Polymer
LW	LayerWise
XFEM	eXtended Finite Element Method

Paper C

AFEM	Augmented Finite Element Method
CZ	Cohesive Zone
DOF	Degrees Of Freedom
ESL	Equivalent Single-Layer
FE	Finite Element
FEM	Finite Element Method
FRP	Fibre-Reinforced Polymers
LW	LayerWise
PNM	Phantom Node Method
SAE	Society of Automotive Engineers
TCB	Triple Cantilever Beam
XFEM	eXtended Finite Element Method

Paper D

CZ	Cohesive Zone
DOF	Degrees Of Freedom
ESL	Equivalent Single-Layer
FC	Fibre Compression
FE	Finite Element
FRP	Fibre-Reinforced Polymers
FT	Fibre Tension
LDR	Local Delamination Ratio
LW	LayerWise
MC	Matrix Compression
MCID	Matrix-Crack Induced Delamination
MT	Matrix Tension
SAE	Society of Automotive Engineers
TSL	Traction-Separation Law

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	Johannes Främby, Jim Brouzoulis and Martin Fagerström. Assessment of two methods for the accurate prediction of transverse stress distributions in laminates. *Composite Structures* 140:602-611, doi: 10.1016/j.compstruct.2015.12.036. Reprinted with permission.
Paper B	Johannes Främby, Martin Fagerström and Jim Brouzoulis. Adaptive modelling of delamination initiation and propagation using an equivalent single-layer shell approach. *International Journal for Numerical Methods in Engineering* 112(8):882-908, doi: 10.1002/nme.5536. Reprinted with permission.
Paper C	Johannes Främby, Martin Fagerström and Jesper Karlsson. An adaptive shell element for explicit dynamic analysis of failure in laminated composites Part 1: Adaptive kinematics and numerical implementation. *To be submitted*
Paper D	Johannes Främby and Martin Fagerström. An adaptive shell element for explicit dynamic analysis of failure in laminated composites Part 2: Progressive failure and model validation. *To be submitted*

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work, *i.e.* planning, developing theory, making the numerical implementations, performing simulations and writing of the papers, all with the assistance of the co-authors.

Contents

Part I
Extended Summary

1 Background

In the 2011 European Union White Paper on transportation [1] it is stated that the CO_2 emissions from the transportation sector shall be reduced by 60 % in 2050 compared to 1990. This type of statement is part of a global trend where the emissions of green house gases from transportation are being targeted by regulatory bodies. Since the emission of CO_2 is directly linked to the fuel consumption of internal combustion engines, decreasing fuel consumption is crucial.

An important factor for the vehicle fuel consumption is the weight of the vehicle. In the investigation by Park *et al.* [2] it was reported that an estimate of 75 % of the fuel consumption of a passenger car can be directly related to its weight, and that a 6-8 % increase in fuel economy can be realised for every 10 % reduction in vehicle weight.

Due to the regenerative capabilities of electric engines, decreasing the weight of an electric vehicle will reduce its energy consumption but not to the same extent as for a vehicle powered by an internal combustion engine. Nevertheless, decreasing the energy consumption allows for increased electric driving range making low vehicle weight almost equally important for these types of vehicle [3].

Park *et al.* [2] also concluded that replacing steel materials in structural components with polymers, Fibre-Reinforced Polymer (FRP) and especially laminated composites of continuous Carbon Fibre-Reinforced Polymer (CFRP) have the potential of effectively reducing the weight of vehicles. This is due to the high specific stiffness and strength of these materials (stiffness and strength per unit weight), which is illustrated in Figure 1.1. Similarly, in the report by Heuss *et al.* [4] it was estimated that laminates of continuous CFRP (*composites* in the following) have the potential of reducing the weight of vehicles by 50 % compared to steel and that the emission reductions from improving the powertrain efficiency will not alone be sufficient in order to fulfil regulatory demands past 2021. It should also be mentioned that the reduction of the structural weight can result in secondary savings, *e.g.* smaller powertrain, brakes, *etc.*

Driven by these conditions, the automotive industry is currently very active in research to incorporate composite materials into structural components, in order to reduce the weight of their vehicle fleet.

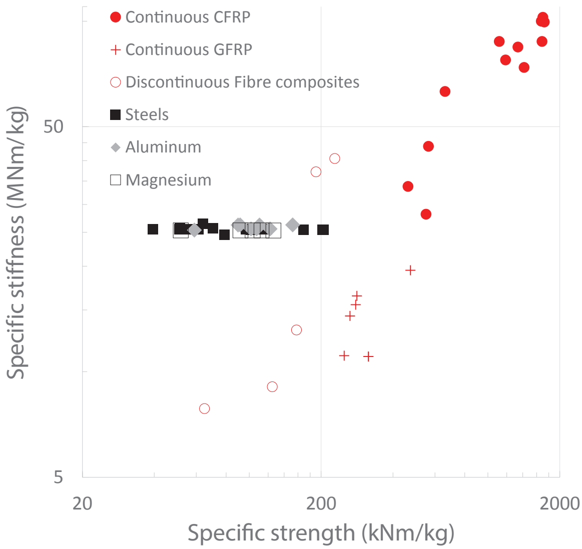


Figure 1.1: *Chart over specific stiffness and specific strength for different material groups. NB: logarithmic scale. © 2016 Henrik Molker. Reprinted with permission from thesis by Molker [5].*

2 Challenges for introducing composites in automotive structures

Compared to traditional materials used in the automotive industry, *e.g.* advanced steels of different grades and light-weight metals such as aluminium and magnesium, the cost of raw material in composite components is very high. According to the thesis by Hagnell [6], cost of material is the dominating cost driver at 50-90% of the total part cost. In addition, the manufacturing of composites components is generally more labour intensive and thus more expensive compared to metallic counterparts. Heuss *et al.* [4] exemplified this for an automotive fender, where the cost of manufacturing this from composites was 570 % to that of the steel version. However, [4] also conclude that this cost will likely decrease over time. For example, the research by Hagnell [6] and Mårtensson [7] aim to provide the industry with tools for achieving cost effective design of components made of composites.

There are indeed multiple challenges for introducing composites in automotive structures. Apart from high costs, issues like material sourcing, quality assurance, material variability, recycling, *etc* must be addressed if composites are to have a future in automotive structures. However, this thesis will focus on the challenge related to the design and development of automotive structures and in particular on crashworthiness assessment.

2.1 Design and development tools for composite structures

Due to the high costs, composite materials have historically been used mainly in the aerospace industry where the allowable cost increase per saved kilogram is high. The Computer Aided Engineering (CAE) virtual design tools for developing composite structures are therefore primarily tailored to the specific needs and requirements in the design of aerospace structures.

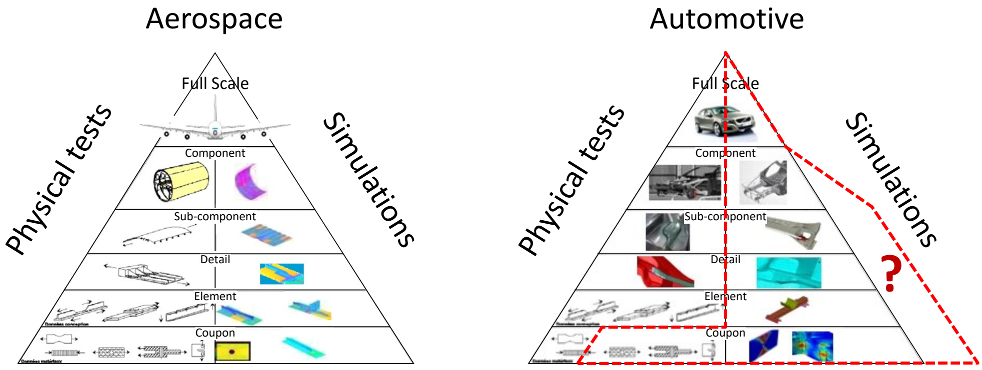
In the aerospace industry a building block approach (BBA) [8] is used to ensure that secondary loads, associated with the many potential failure modes in composite materials, are not critical for the design. This approach relies heavily on physical validation testing on different structural levels: material coupon, element, detail, subcomponent and component levels, as illustrated in Figure 2.1a. Development using this approach is therefore very costly and time consuming.

On the contrary, the development of modern automotive vehicles is almost exclusively driven by CAE, and especially using numerical finite element (FE) simulation tools. Basically, physical testing (besides the full-scale vehicle crash tests like the different NCAPs) is only performed on or close to the material coupon level. From this level data is then used to define the properties of material models used in simulations on higher structural levels. If composite materials are to become widespread in automotive vehicle structures the product development process of such components needs to be in line with that of the automotive industry. This is illustrated in Figure 2.1b, where it is indicated that the development of composite automotive structures can only rely on a limited amount of physical tests, performed on the material coupon scale.

One effort to achieve an efficient and reliable design methodology for automotive composite structures has been proposed in the thesis by Molker [9]. This design methodology can be seen as a streamlined aerospace BBA where intermediate structural levels are only analysed if necessary. However, this approach is not intended to assess the crashworthiness of composite structures since it relies on an uncoupled global-local strategy. Furthermore, as in the design of aerospace structures, the evaluation is made in relation to the initiation of failure and not to any subsequent damage progression – a phenomenon which needs to be captured in crash simulations. In general, the crashworthiness of aerospace structures is only assessed to a small extent compared to that of automotive structures. Consequently, no suitable numerical FE tools capable of assessing the crashworthiness of composite automotive structures have been developed.

2.2 Composites in crash

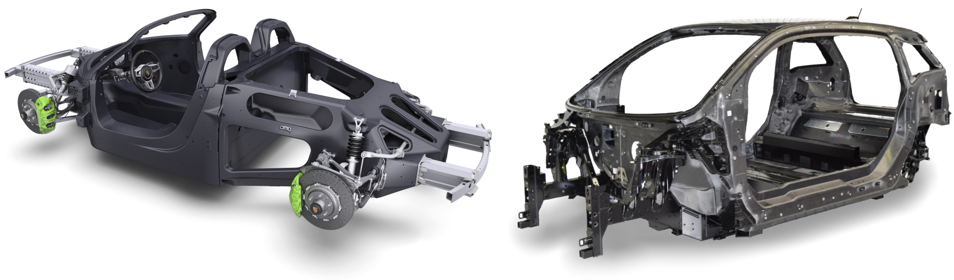
A consequence of not having FE tools for crash simulations of automotive composite structures can be observed by examining modern passenger cars made of composite materials, as exemplified in Figure 2.2. Here the main passenger protection compartment is made of composite materials. This compartment is primarily designed to be stiff and prevent intrusion in the event of a crash, *i.e.* the structure is not intended to deform to any large extent. Instead, the crash protection structures, which through severe deformation



(a) (b)

Figure 2.1: *Rouchon's testing pyramid for the development of composite structures in the aerospace industry (a) and translated to the automotive industry (b). The red line indicates the ambition to perform limited amount of physical testing only on the material coupons and perform (additional) simulations on superior levels, including full scale. Adapted from [10] and [11].*

will dissipate kinetic energy in the event of a crash, are made of metallic material.



(a) (b)

Figure 2.2: *Examples of body structures with a composites main passenger compartment and metal front and rear crash protection structures in the Porsche 918 Spyder [12] (a) and the BMW i3 (b).* © *2016 Porsche Cars North America and* © *2015 FKA*

The split composite/metal design is a consequence of the lack of crash simulation tools for composite materials and not because these materials are inappropriate to use in crash protection structures. On the contrary, as concluded by *e.g.* Hamada *et al.* [13], composite structures can be tailored to achieve high Specific Energy Absorption (SEA), *i.e.* energy absorption (dissipation) per unit weight. In axial compression, the SEA of composites can be significantly higher compared to the aluminium and steel grades normally used in crash protection structures.

It has been shown by *e.g.* Hull [14] and Grauers *et al.* [15] that the high SEA of composites is the consequence of a very complicated fracture process of the material. This so-called crushing process involves many competing failure mechanisms, *e.g.* compressive fibre kinking, compressive matrix failure and significant (mixed-mode) delamination, which is illustrated by an example in Figure 2.3. Most of these failure modes are not present in the failure of metal structures. Thus, these characteristics cannot be captured with existing FE models intended for crash simulations of metallic structures. The challenges in developing models which are appropriate for performing crash simulations of automotive composite structures are indeed many and complex and will be the topic of the next chapter.

I end this chapter by referring to the EU report European Roadmap to Safe Road Transport [16], where they conclude that the development of FE tools for the accurate prediction of the crash response of vehicle structures in laminated composites is crucial for structural composites to have a widespread use in future automotive vehicles.

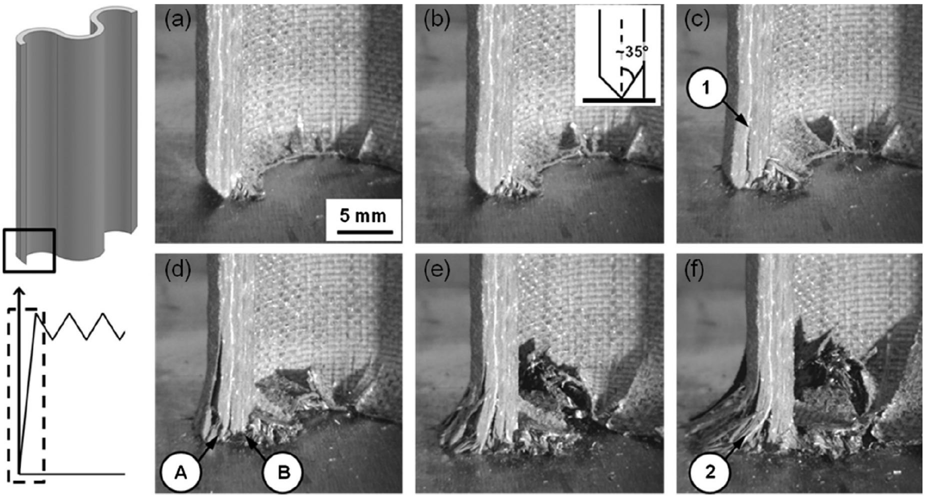


Figure 2.3: *Example reproduced from [15] on crushing of laminated composites; including bending of plies Ⓐ, compressive failure Ⓑ, delamination in mode I ① and in mixed mode ②. The upper left image illustrates the test geometry and the location of the specimen in (a-f). The lower left image illustrates the corresponding location in a typical force versus displacement curve. © 2013 Elsevier Ltd. Reprinted with permission.*

3 Research challenges for crash modelling of composites

The experimental example in Figure 2.3 illustrates the many competing failure mechanisms active during crushing of laminated composites. In the crushing zone, schematically illustrated in Figure 3.1, the bending and compressive failure of the laminate are the results of a combination of different intralaminar (within the plies) and interlaminar (between the plies) failure modes.

The intralaminar failure modes are associated with the anisotropic and heterogeneous architecture of the composite plies, which for unidirectional (UD) composites generally can be divided into two major categories:

- Longitudinal failure occurring from loads mainly parallel to the fibres:
  - Tensile fibre failure (Figure 3.2a) – the tensile load is carried by the fibres up to their strength, which is then followed by catastrophic failure.
  - Compressive fibre failure (Figure 3.2b) – likely the most complex failure mode due to shear failure of the matrix and friction between crack surfaces, often with subsequent finite rotation the fibres in so-called kink bands.
- Transverse failure occurring from loads mainly perpendicular to the fibres. Due to the low strength of the matrix, transverse failure is affected by shear loads to a larger extent than longitudinal failure modes. Depending on the stress state, cracks can form at different angles, however, they can be categorised as:
  - Tensile matrix failure (Figure 3.2c) – stress concentrations in the matrix material around fibre inclusions lead to low failure strength in this mode;
  - Compressive matrix failure (Figure 3.2d) – complex failure mode involving shearing of the matrix and friction between crack surfaces.

A further complication to the matter is that most of the failure modes can interact and theoretically occur simultaneously.

When stacking plies in a laminate, the interfaces between the plies can be the origin of interlaminar failure, *i.e.* delamination. This problem is pronounced if there is a large difference between fibre angles of adjacent plies, which is almost always the case in laminated composite structures.

Delamination propagation can be classified according to the load type and its orientation with respect to to the propagation direction. In most cases it is difficult to define the in-plane propagation direction of the crack front, making it difficult to distinguish between mode II and III growth. Therefore a common practise is to treat mode II and III growth as one and the same shearing mode.

In the progressive failure of composites, microscopic intra- and interlaminar failure can easily lead to failure on the laminate level. So, to be able to make accurate prediction of the crashworthiness of an arbitrary composite structure, all of the above mentioned failure modes must be taken into account. However, as mentioned previously, the failure

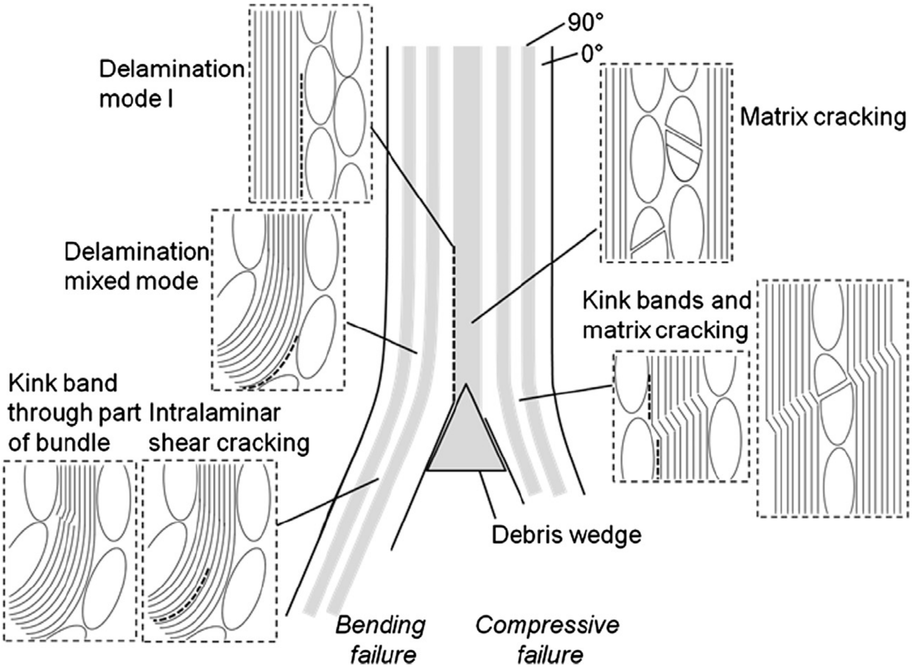


Figure 3.1: *Schematic illustration of a crushing zone in a laminated composite [15]. The failure includes both bending and crushing on the laminate scale as well as inter- and intralaminar failure on the ply scale. © 2013 Elsevier Ltd. Reprinted with permission.*

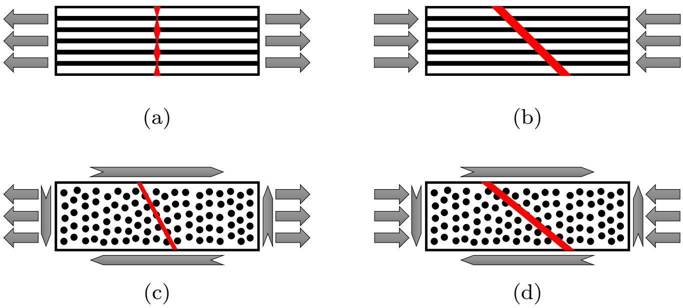


Figure 3.2: *Different intralaminar failure modes of a unidirectional composite: Longitudinal tensile (a) and compressive (b) fibre failure, transverse tensile (d) and compressive (e) matrix failure.*

of metals are not distinguished into intra- and interlaminar failure modes. Thus, new models which are appropriate for performing crash simulations of automotive composite structures must be developed.

When assessing the crashworthiness performance of automotive vehicles, the crash

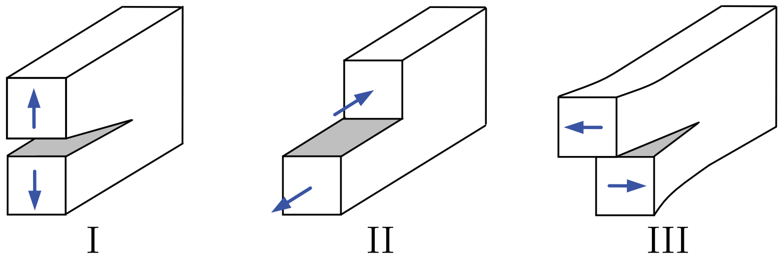


Figure 3.3: *Schematic illustrations of crack propagation in (I) peeling (II) shearing and (III) tearing mode, from [17].* © *2008 Elsevier Ltd. Reprinted with permission.*

simulations must to a large extent be performed on large FE models of the full-scale vehicle. Even considering state-of-the-art simulations of metallic structures, when most of the structure is modelled using equivalent single-layer (ESL) shell elements, the number of elements are in the order of millions. This, in combination with the relatively long time period that needs to be simulated (typically in the range of 100-300 ms), means that crash simulations are solved using large computer clusters, where there is a practical limit on how many computer cores the simulation can be divided to. Consequently, there is a requirement to keep the size of the FE models limited - preferably such that the CAE-engineer can have the results from a crash simulation over one or two nights.

Even if using a ply material model that can take all the intralaminar failure modes into account, ESL shell elements cannot accurately resolve the stress state such that the correct failure modes on the ply level are predicted [18]. Furthermore, since the ESL shell element represents the entire thickness of the laminate, the kinematics of delamination crack growth cannot be described. This is particularly problematic since delaminations are one of the governing failure modes, in the sense that propagating delaminations significantly influence the overall deformation pattern and thereby indirectly, the occurrence of the other failure mechanisms, cf. Grauers *et al.* [15]. It is therefore clear that in order to achieve accurate predictions of the crashworthiness performance of laminated composites in simulations, the delamination process needs to be explicitly accounted for in an accurate way without compromising the computational efficiency too much.

3.1 Modelling approaches

The numerical approaches to modelling laminated composites in crash simulations can generally be divided into two categories where the focus is on either efficiency *or* accuracy[1]. With focus on efficiency, ESL models with one element through the thickness (cf. Figure 3.4a) are used together with phenomenological material models. These are models which are not based on the physical mechanisms but rather mimicking the total failure process including the effects of delamination, cf. *e.g.* Feraboli [21] and the CZone technology [22]. This efficient approach, which is similar to the state-of-the-art crash

[1]I acknowledge that this is in no way an exhaustive description on the subject of modelling laminated structures and refer to the reviews by Carrera [19], Orifici etal [17] or Kreja [20] for further reading.

simulations of metals, requires extensive physical testing on the laminate level and the response of a laminate with an arbitrary layup cannot be predicted.

With more focus on accuracy, high-fidelity LayerWise (LW) models are adopted. Here, each individual ply is represented by a layer of separate elements (cf. Figure 3.4b). To account for delaminations, the interfaces are modelled by means of an interface cohesive zone (CZ) law in the form of interface elements or similar, cf. *e.g.* Greve and Pickett [23] or Tan *et al.* [24]. This approach, which often is adopted in aerospace impact simulations (cf. *e.g.* Lopes *et al.* [25]), is generally able to accurately describe the failure process in laminated composites. However, the high resolution requires several orders of magnitude additional elements and a smaller computational time step compared to the efficient ESL approach. This leads to extreme computational times, making industrial crash simulations infeasible.

An option to improve the computational efficiency of LW models is to only model sublaminates (instead of individual plies) with separate element layers. Again, the element layers can be connected by cohesive interface laws to account for delamination, cf. *e.g.* Hörmann and Wacker [26] or Bussadori *et al.* [27]. Please note, that each sublaminate can be modelled by individual ESL models, but since these are stacked on top of each other this approach is still considered a LW model (cf. Figure 3.4c). A problem with this approach is that it requires *a priori* assumptions on which interfaces that will be able to delaminate during simulations and cannot be truly predictive for the general case.

A major research challenge for crash failure analysis of laminated composites is thereby to find a modelling approach which is both sufficiently accurate in predicting the structural response *and* computationally efficient – a challenge addressed in this thesis.

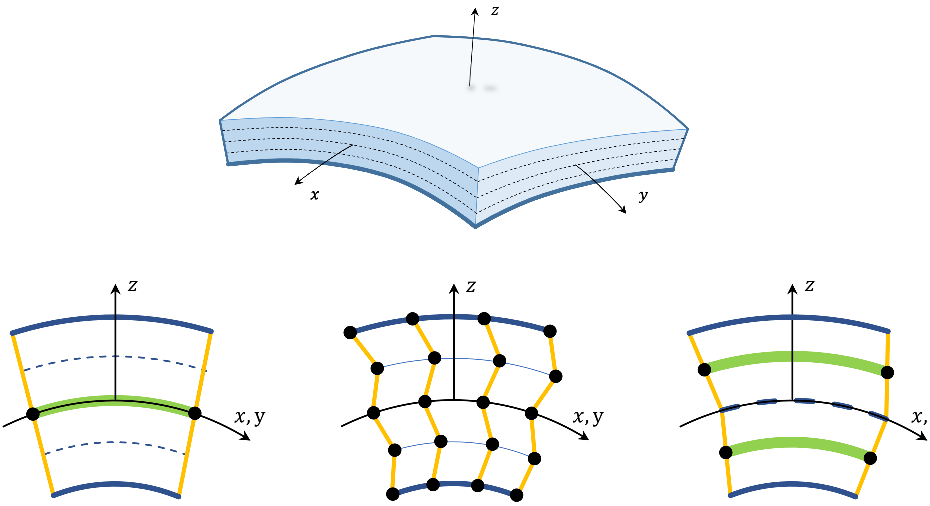
3.2 Research scope

To be able to perform large-scale simulations of progressive failure in laminated composites while maintaining a good level of predictability (*e.g.* ability to capture delamination), new types of FE models need to be adopted. These models must be able to combine computational efficiency *and* accuracy. A solution to reduce computational cost, while maintaining the accuracy of high-fidelity models, is to resort to an adaptive modelling technique, where an initially coarse model can be locally refined during the simulation.

To achieve this, the idea in this research has been to maintain the numerically efficient ESL shell formulation for the initial modelling of the laminated structure. During the simulation the elements can be locally refined, by extension of the element formulation, when the damage state no longer can be represented by the simplified ESL model. This way, the increased computational cost, associated with the analysis of progressive damage in laminated composites, is limited both in time and to the pertinent areas of the FE model.

The refinement is twofold. Firstly, by refining the element through the thickness the accuracy of the stress state prediction can be improved. Secondly, the kinematics of the ESL shell element must be extended in order to accurately model delamination cracks. In other words, the refinements locally transform the ESL model to a LW instead.

In order to predict the areas in need of refinement, different types of refinement



(a) (b) (c)

Figure 3.4: *Examples of modelling approaches for laminated composites. (a): Equivalent single-layer model where the entire laminate is represented by one midsurface element (green line) having delaminations accounted for by using phenomenological laminate material models. (b): Layerwise model where each ply is represented by a separate layer of elements using a ply material model. To account for delaminations the plies can be interconnected by cohesive laws. (c): Layerwise model where sublaminates are represented (possibly by equivalent single-layer models) instead of individual plies. The sublaminates can be interconnected with cohesive laws.*

indicators can be used to make an assessment of the error in the initial coarse ESL model. For example, an indicator could be to approximate the correct stress state and compare this to the stress state predicted by the ESL shell element. If there is a large discrepancy between the states, the element should be refined.

The research presented in this thesis has been conducted in a project where the aim is to deliver results that can be utilised by the automotive industry (cf. next Section). Due to the extreme level of complexity, industrial full-scale vehicle crash simulations are almost exclusively performed using commercial dynamic explicit FE solvers. Besides being easily available for industrial use, any adaptive technique must therefore also be suitable for this type of solver. This creates challenges since explicit solvers are very sensitive to modifications during the simulation. For example, refinements can result in a sudden change in the discretised internal forces, which may cause non-physical oscillations in the model. Such oscillations must therefore be minimised. Consequently, besides yielding accurate results and being computationally efficient, the implementation must be numerically robust.

In summary, this thesis will address the following challenges:

1. Develop a computationally efficient adaptive technique, where an initial coarse

model can be locally refined to improve the accuracy of the predicted response. This includes both improving the accuracy in predicting the correct stress state and the ability describe the kinematics of propagating cracks like delaminations.

2. Develop indicators that can asses when the element should be refined. This include a technique to improve the prediction of stress state in ESL shell models.

3. Make the adaptive technique available for industrial use in commercial crash simulation FE solvers.

The last point is especially challenging since access to the source code to make necessary modifications to commercial software is often restricted. This introduces limitations on the user friendliness and how well the computational efficiency of an adaptive technique can be exploited. Focus in this thesis is therefore to demonstrate the possibilities of performing adaptive industrial crash simulations, while acknowledging that high computational efficiency might not be achieved at the moment.

Evident from the list above is also that this thesis does not address the development of better suited ply material models. However, the current research is part of a cluster of projects where also other aspects of developing suitable crash simulations models are addressed. A brief overview of these projects will be given in the next section.

3.3 Research project

The research presented in this thesis is part of two consecutive projects *Modelling crash behaviour in future lightweight composite vehicles — Step 1 and 2*. The main goal of the projects has been to develop computational efficient numerical FE tools for the accurate prediction of the crash response of composite structures. The projects have been divided into different work packages (WPs) and the research covered by this thesis primarily consists of one WP from each of the projects, as illustrated in Figure 3.5. Figure 3.5 also shows the different partners involved as well as some of the closely related research projects on crash modelling of composites, Compcrash 1 and 2 [28, 29] and the EU project ICONIC [30]. The research in these projects focus on ply material models for crash simulations and are thus intended to complement the adaptive modelling methods presented in this thesis.

The projects mentioned above includes some of the Swedish efforts on developing models for analysing progressive failure of composites. The research results presented in this thesis is found in the appended papers, however, in the next chapter I will attempt to summarise the key findings. While these results only constitutes some aspects of the overall research efforts, I believe they are essential ingredients in order to be able to perform industrial crash simulations of laminated composites.

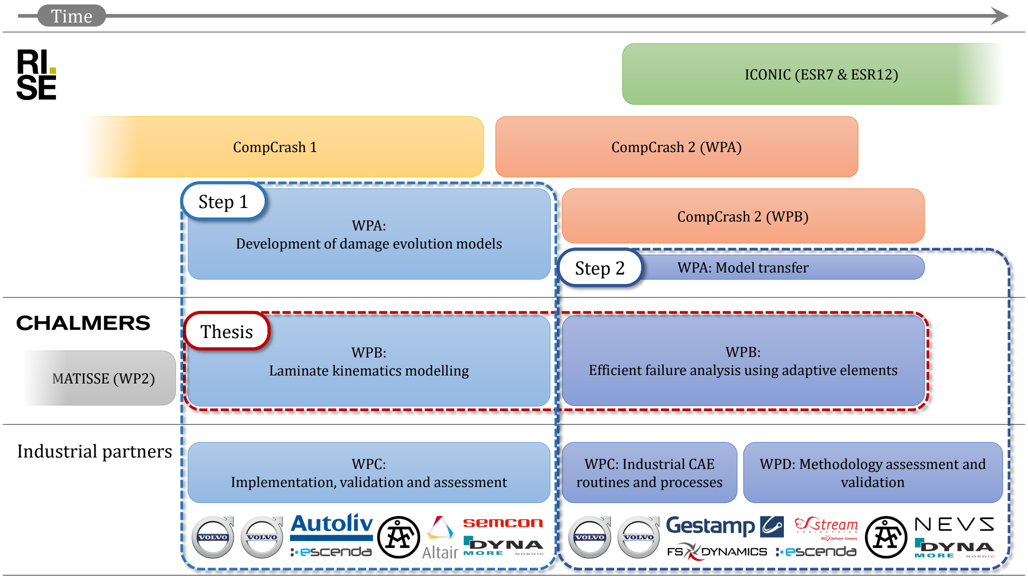


Figure 3.5: *Schematic illustration of the two research projects* Modelling crash behaviour in future lightweight composite vehicles — Step 1 and 2 *(marked in shades of blue), where the current thesis covers work packages B. Besides the thesis projects, other closely related research projects on crash modelling of composites at RISE Sicomp are shown. In addition, it is indicated that developments made in the EU project MATISSE [31] served as a starting point for the research in this thesis. Please note that the sizes of bubbles and company logos do not necessarily reflect the resources spent in the projects.*

4 Proposed method for crash modelling of composites

The main research challenge addressed in this thesis is to develop an adaptive modelling method for achieving computationally efficient and accurate crash simulations of laminated composites.

The proposed method consists of the following steps:

i The laminated structure is initially represented by a single layer of ESL shell elements through the thickness.

ii Refinement indicators are used to locate areas which need to be refined in order to achieve an accurate response.

iii The shell elements are locally refined through the thickness by enriching the element kinematics to account for material interfaces (weak discontinuities).

iv At interfaces prone to delaminate, interface CZ elements are inserted such that delaminations (strong discontinuities) can initiate.

v If the initiated delaminations propagate, the enrichment areas are expanded such that the fracture process can be accurately resolved.

The main idea is that, by initially representing the laminated structure by a single layer of shell elements, a computationally efficient model can be constructed. During loading, the model is then locally refined in critical areas where the simplified element kinematics cannot accurately resolve the fracture process. In this way the additional computational expense, associated with the complicated fracture process in laminated composites, can be limited while a high level of accuracy is still maintained. In the following, the first refinement step, where material interfaces are added through the thickness, will be referred to as *weak refinements*. The secondary refinement step, where CZ elements are inserted, will be referred to as *strong refinements*

In order to limit the computational costs, the proposed method only allows through-the-thickness refinements, *i.e.* no in-plane refinements are made. Thus, while interlaminar fracture can be explicitly modelled (with strong refinements), intralaminar cannot. Instead, it is assumed that the intralaminar behaviour is modelled using a ply material model, *e.g.* the smeared-crack model from Compcrash [29]. However, the proposed adaptive method is not dependent on a particular type of intralaminar material model.

When adopting a smeared crack material model, this needs to be regularised such that the correct amount of energy is dissipated. In **Paper D**, we demonstrate the importance of considering both the element size and the crack orientation when properly regularising such smeared crack models.

Intralaminar matrix cracks, which can form at comparatively low loads, are common initiation points for delamination. In Figure 4.1 the process of so-called Matrix-Crack Induced Delamination (MCID) is illustrated, where high interlaminar shear stresses at the vicinity of a matrix crack tip lead to the initiation of delaminations. Capturing

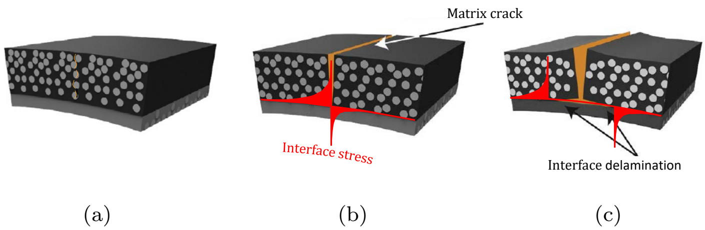


Figure 4.1: *The process of matrix-crack induced delamination. (a): First, a transverse matrix crack starts to form. (b): When the matrix crack is fully evolved it will lead to a shear stress concentration at the interface. (c): If the shear stresses are high enough delaminations can propagate. Adapted from Mortell et al. [32].*

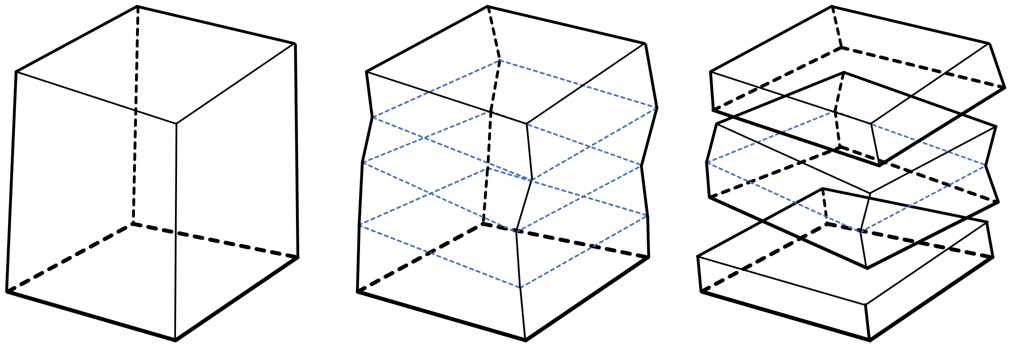
the interaction of intra- and interlaminar failure is challenging when using a smeared crack approach to model the intralaminar fracture. This since there will be no explicit intralaminar crack present to generate a stress concentration. In **Paper D**, we therefore adopted an intra- and interlaminar interaction approach suggested by Yun *et al.* [33]. This interaction works by degrading the critical fracture energy of a CZ element by the damage state of the adjacent intralaminar elements.

4.1 Adaptive element kinematics

The core of the method is based on an element with kinematics that can be adaptively enriched. That is, the initial kinematic assumptions of the element can be relaxed by adding extra Degrees Of Freedom (DOF). For this particular method, where laminated structures are modelled, extra DOF are added such that a through-the-thickness refinement of the element is achieved. The adaptive element can therefore be in one of three stages: a) Unrefined; b) Weakly refined in one or several material interfaces; c) Weakly or strongly refined in one or several interfaces. This is illustrated in Figure 4.2 for a solid shell element, *i.e.* a shell element with eight (initial) vertex nodes.

I want to emphasise that the proposed concept is not restricted to a particular element formulation or refining enrichment method. For example, in **Paper B** adaptive through-the-thickness refinements are achieved via the eXtended Finite Element Method (XFEM) [34, 35] and in **Papers C-D** via the Augmented Finite Element Method (AFEM) [36]. Also other approached *e.g.* the phantom node method [37] or the floating node method [38] or even methods based on isogeometric analysis [39] can be utilised. The important aspect is, once again, that an initial, computationally efficient, kinematic assumption can be relaxed such that the resolution can be increased when necessary. Similarly, different element formulations are used in **Paper B** and **Papers C-D**, respectively. However, both formulations are based on an ESL model, which I strongly recommend to use when slender structures like laminated composites are to be modelled.

The adaptive method had its starting point in developments made in the EU project



(a) (b) (c)

Figure 4.2: *The different refinement stages of the adaptive elements. (a): In the unrefined stage the entire laminate is represented by one element through the thickness. (b): The element can be through-the-thickness refined in order to model weak discontinuities, here exemplified with three refinements. (c): The refined interfaces from the previous stage can be released (and have CZ elements added) in order to model strong discontinuities.*

MATISSE [40]. Therein, two ESL shell elements with enrichable[1] element kinematics were developed. Brouzoulis and Fagerström [41] and Brouzoulis *et al.* [42] developed a shell element which could be enriched via the XFEM to model first interlaminar and later interacting inter- and intralaminar fracture. In **Paper B** this element was used to implement an adaptive method in the open-source software OOFEM [43]. This method does not include the intermediate weak refinement step. Instead, strong refinements are introduced immediately.

A drawback of the adaptive method in OOFEM is that it uses an implicit solver, which is unsuitable for crash simulations. The continued work in **Papers C-D** were therefore instead based on a first commercialisation of the developments in MATISSE. This solid shell element, initially enriched with one centrally-placed strong discontinuity via the AFEM, was implemented as an user element in LS-DYNA [44][2]. In **Paper C** the element kinematics were extended to allow multiple weak and strong refinements, arbitrarily placed through the thickness. In addition, the ability to activate refinements during the simulation was added.

Despite differences in the OOFEM and LS-DYNA adaptive methods, they both assume that the through-the-thickness integration scheme does not change during refinements. For the laminated structure each ply is represented by one layer of integration points (IP) through the thickness. Thus, in the unrefined stage all ply IP are included in one through-the-thickness element. When a refinement is activated, the ply IP below the refinement are assigned to a lower sublaminate and those above to an upper sublaminate.

[1]Non-adaptive since the elements could only be initially enriched.

[2]While LS-DYNA is indeed a well-accepted industry tool for performing automotive crash simulations, the choice of this particular commercial solver was also due to the fact that DYNAmore Nordic AB was the main software partner for Step 2 of the research project, cf. Section 3.3.

That is, no new IP are defined and no mapping of IP data is required. Further refinement of a sublaminate would divide the ply IP to new sublaminates below and above the refinement. This subdivision of the ply IP is exemplified in Figure 4.3.

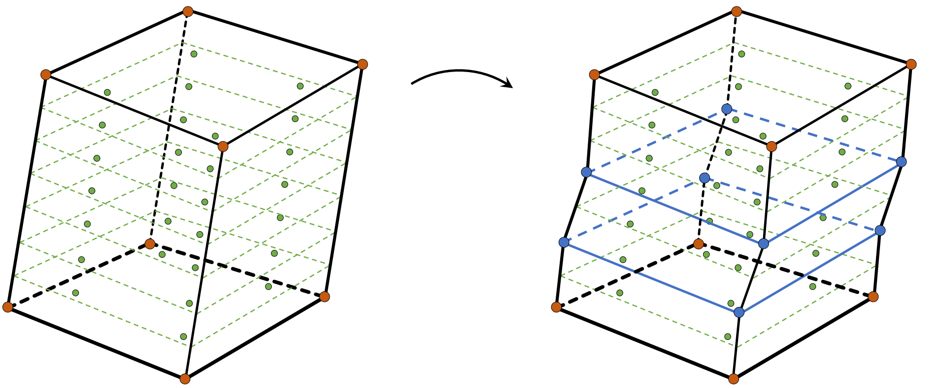


Figure 4.3: *Example of how an unrefined element with seven plies, with one layer of integration points each (left), is subdivided into sublaminates when the element is refined in interface two and four (right). The bottom two plies will be associated with the bottom sublaminate, plies three and four with the second sublaminate and the top three with a third and topmost sublaminate. This particular example shows refinement enrichments via the AFEM, where the element base (vertex) nodes are indicated with orange and the extra nodes with blue.*

4.2 Adaptivity management

The ability to adaptively refine the elements during a simulation require a management system, which will be the focus of this section. First, I will present different refinement indicators, which are used to control when and where refinements should be activated. Secondly, I will show how the refinement extensions can be controlled.

4.2.1 Refinement indicators

The purpose of the refinement indicators is to assess whether a current refinement level is sufficient in order to make an accurate prediction of the fracture process.

Generally, the in-plane stresses are predicted with satisfactory accuracy when using ESL elements, while the prediction of the transverse (out-of-plane) stresses is poor. In **Paper A**, we presented a post-processing stress recovery technique, which was further developed in **Paper B**. This stress recovery technique is computationally inexpensive, seemingly robust and allows for accurate predictions of the transverse stress distribution. The drawback of the technique is that it can only be used in a post-processing step. The recovered stress state can therefore not be used as input to a material model. However, by evaluating intra- and interlaminar failure initiation criteria using the recovered stress state, indicators for the activation of weak and strong refinements can be constructed.

Even if an element is fully refined, MCID (cf. Figure 4.1) cannot be predicted since the intralaminar cracks are not explicitly modelled. The stress-based refinement indicators presented above were therefore completed with a damage-based indicator in **Paper D**. The damage states of all plies are monitored and if the damage in a ply reaches a certain limit, indicating that a matrix crack is forming, strong refinements are activated in the adjacent interfaces.

I want to emphasise that the indicators mentioned above are just some examples of possible indicators used to activate refinements. The important thing is to have refinement indicators such that the refinements can be introduced before any failure is initiated (both in the unrefined and the refined state of an element). This way, sudden jumps in the stress state upon refinement can be minimised.

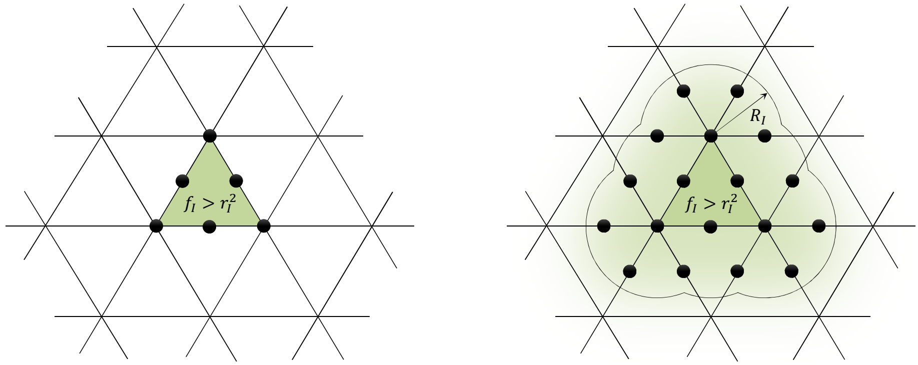
4.2.2 Refinement size management

When an indicator specifies activation of an interface refinement in an element, the element in-plane neighbours must also be (at least partly) refined. Otherwise, the continuity of the refinement cannot be kept. In addition, the purpose of the refinements is to relax the kinematic constraints of the elements such that higher resolution can be achieved. So, if the refinement patch size (in-plane extension) is too small, surrounding unrefined elements can still constrain the desired relaxation. However, if the refinement patch is too large this will add unnecessary computational expenses.

In **Paper B**, we investigated the required size of the refinement (enrichment) patch, both with respect to the initiation and to the propagation of delaminations. When the indicator for high transverse stresses is activated in an element, all element nodes within a certain radius from the element are enriched, cf. Figure 4.4. An expansion indicator, based on the presence of cohesive damage in the refined elements, is then used to asses whether the delamination is starting to propagate. If this is the case, the enrichment patch is expanded to include the element nodes within a certain radius, cf. Figure 4.5.

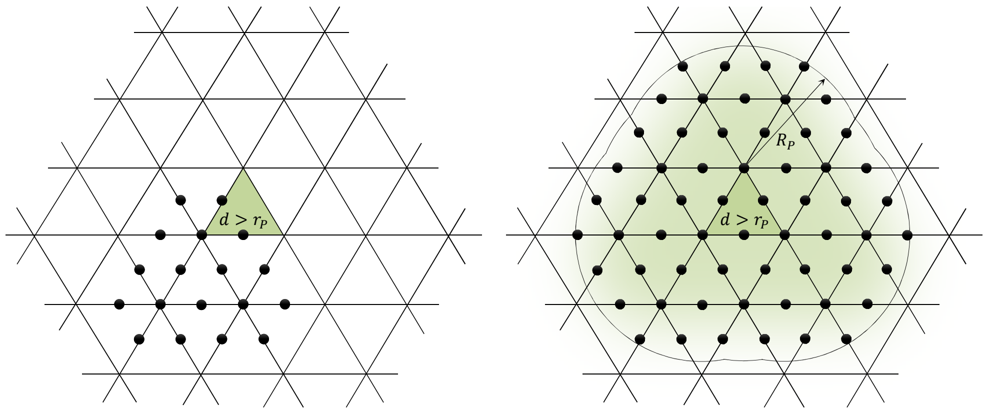
In **Paper B**, the refinements are made via the XFEM, where the deformation is subdived into one continuous and one discontinuous field. Therefore, it is easy to guarantee continuity at the refinement boundary since only the nodes inside the refinement patch are enriched with the discontinuous field, cf. Figure 4.6a.

On the contrary, in **Papers C-D** the refined element is divided into subelements via the AFEM, which does not allow for a simple way to guarantee continuity at the refinement boundaries. In this method, the subelements are defined by adding global extra nodes, which are shared between neighbouring elements. Thus, if the extra nodes are unconstrained at the refinement boundary, continuity is not achieved, cf. Figure 4.6b. It is not straightforward to constrain the shared extra nodes in a user element and this feature has therefore not been added in the LS-DYNA implementation. Instead, the refinement patch includes all in-plane neighbouring elements in the model.



(a) (b)

Figure 4.4: *When the indicator for high transverse stresses f_{I} is activated in an element, the associated element nodes are enriched (a) along with the nodes within an in-plane radius R_{I} (b).*



(a) (b)

Figure 4.5: *When cohesive damage d reaches a certain value r_{P} in an element in the refinement patch (marked by •) the associated element nodes are enriched (a) along with the nodes within an in-plane radius R_{P} (b).*

4.3 Challenges related to using an explicit dynamic solver

In **Papers C-D**, the adaptive method was implemented as a user element in the explicit solver LS-DYNA. Both the weak and the strong refinements can result in sudden changes in the discretised internal forces. Since explicit solvers are very sensitive to sudden changes, this may cause non-physical oscillations in the model. To minimise such oscillations, two

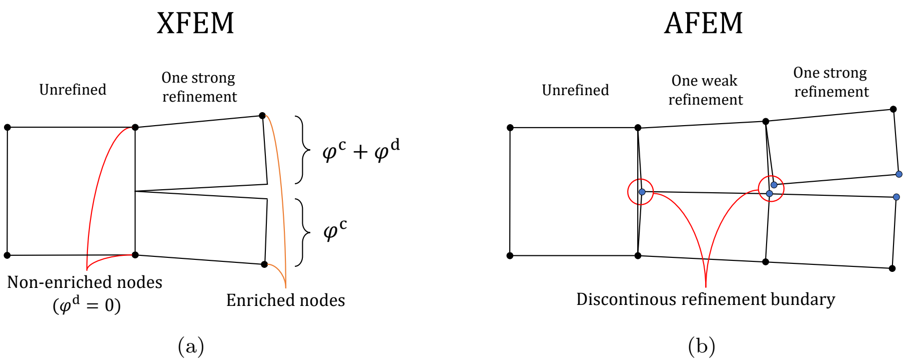


Figure 4.6: *Refinement continuity. (a): In the XFEM, where the refinements are modelled by approximating the deformation from one continuous φ^{c} and one discontinuous φ^{d} field, refinement continuity is guaranteed by not enriching the nodes at the refinement boundary. (b): In the AFEM, the refinement subelements are defined by adding extra nodes (blue) to the element. If the extra nodes are unconstrained at the refinement boundary continuity is not achieved.*

types of damping procedures were proposed in **Paper C**. These will be presented below.

4.3.1 Stabilisation of weak refinements

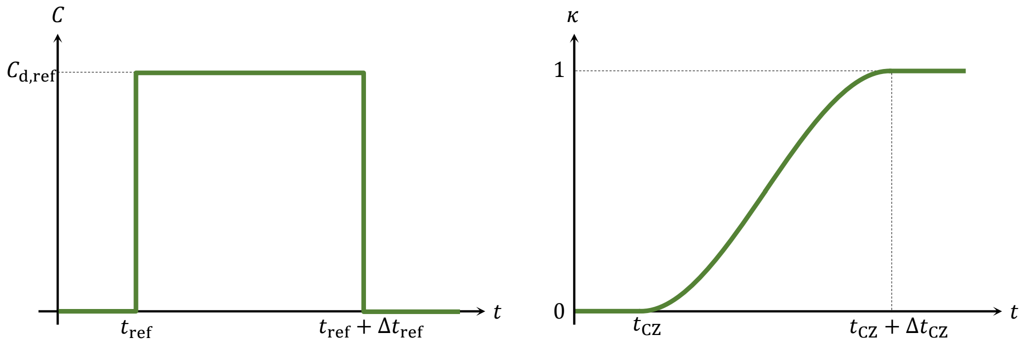
When a weak refinement is activated, the initial positions (and velocities) of the new extra nodes must be interpolated from the closest, already active, nodes below and above. The proposed interpolation is only an estimation and does not necessarily result in balance of linear momentum. The newly introduced nodes will then start to move towards their balance positions, resulting in non-physical oscillations.

In order to stabilise the refinement, a small amount of damping is applied for a short time period directly after the refinement, cf. Figure 4.7a.

4.3.2 Stabilisation of strong refinements

When a strong refinement is activated, the interface of the weak refinement is duplicated and a CZ element is inserted. Just as for the weak refinement, this may cause abrupt changes in internal forces. Instead of applying a damping force also in this case, we follow a method similar to that proposed by Menouillard and Belytschko [45] and apply a correction force to balance the sudden change in internal forces. The purpose of the correction force is to tie the node pairs of the two coincidental interfaces together, *i.e.* the separate node pairs shall move as if they were one node in each time step.

Following [45], the release of the strong refinement is then made by gradually degrading the correction force over a short time period, cf. Figure 4.7b. This way the CZ element is introduced smoothly.



(a) (b)

Figure 4.7: *Stabilisation of refinement. (a): Damping function employed to stabilise the weak refinement, where* $C_{\mathrm{d,ref}}$ *is the damping value,* t_{ref} *is the time of refinement and* Δt_{ref} *is the duration of the damping. (b): Weight function* $(1-\kappa)$ *to gradually release the node pairs of the strong refinement, where* t_{CZ} *is the time of refinement(CZ element introduction) and* Δt_{CZ} *is the duration of the transition.*

5 Concluding remarks

If structural composites are to become common in future automotive vehicles it is crucial to develop FE tools which are both computationally efficient and can accurately predict their crash response. To be able to make an accurate prediction, important failure modes such as delaminations must be captured by the simulation models.

In Chapter 4, I presented an adaptive method which achieves an accurate prediction in a computationally efficient way. The method is based on a computationally efficient ESL shell formulation. During the simulation, when the damage state no longer can be represented by the simplified ESL model, the shell is adaptively and locally refined by extension of the element formulation. This way, the increased computational cost, associated with the analysis of progressive damage in laminated composites, can be limited both in time and to the pertinent areas of the FE model. The refinement is twofold. Firstly, by refining the element through the thickness, the accuracy of the stress state prediction is improved. Secondly, the kinematics of the ESL shell element is extended in order to accurately model delamination cracks. I emphasise, once again, that the proposed adaptive method is general and can easily be applied to other element formulations and refinement techniques than those adopted in the current work.

In order to limit the computational costs, the proposed method only allows through-the-thickness refinements, *i.e.* no in-plane refinements to model intralaminar fracture are made. Instead, an intralaminar smeared crack material model is used. In **Paper C**, we discuss how the interaction between intra- and interlaminar failure can be considered by coupling the cohesive fracture energy to the intralaminar damage state of the adjacent layers. If this coupling is not present, the damage evolution of the CZ elements is restricted and the correct intra- and interlaminar crack propagation cannot be predicted. Moreover, We show that a mesh-based regularisation of the smeared crack model yields very accurate predictions of the dissipated energy.

To achieve a computationally efficient adaptive method, the refinements should be limited to the vicinity of the area that require increased resolution. As concluded in **Paper B**, the size of the refinement patch should be large enough to allow the fracture process to be accurately resolved and we proposed a suitable size to achieve this. Furthermore, we showed that a criterion based on the interlaminar damage state can be used to indicate when the refinement patch should be expanded. Once delaminations have initiated, the size of the patch must be large enough to facilitate a long enough delamination propagation in each time (or load) step.

In **Papers B-D**, we showed that the proposed method can reproduce similar results as a high-fidelity model while saving computational effort. In an example in **Paper B**, close to 50 % computational time is saved compared to the case where all interfaces are refined during the entire simulation. However, the computational efficiency gain is not as high when using the adaptive LS-DYNA method in **Papers C-D**. This is partly because the latter method does not fully exploit the computational efficiency of the adaptive refinement approach. In contrast to the XFEM based method in **Paper B**, the refinements are made by activating extra nodes (via the AFEM). Unfortunately, all (including the non-active) extra nodes are updated by the LS-DYNA solver during the entire simulation[1]. Furthermore, when refinements are activated, these are not limited to an in-plane patch in the vicinity of the area indicated to be refined. Instead, all in-plane neighbouring elements are refined.

I would like to point out that computational efficiency gain is difficult to measure, since the efficiency is often problem related. On the one hand, a large problem where only small parts need to be refined will show a high computational efficiency compared to solving the same problem using a high-fidelity model throughout the simulation. On the other hand, a similarly large problem where most of the model becomes refined, *e.g.* due to complex loading, will show a lower computational efficiency. Furthermore, the gain in computational efficiency is also depending on the choice of material model and integration scheme, especially when an explicit solver is used. A model with a computationally demanding material model and high number of IP will be computationally expensive, even if all IP through the thickness are included in one element. Refining the element will then not significantly increase the total computational expenses. Nevertheless, an adaptive modelling approach remove the necessity of making a priori assumptions on which parts of a model that require high resolution to achieve accurate results.

Different aspects of the adaptive method have been presented in **Papers B-D**, and I want to stress that the complete method is the total contribution of all these papers. Nevertheless, the aim of the adaptive method is to model fracture of laminated composites in automotive crash simulations, which is why the method was implemented in LS-DYNA (**Papers C-D**). Thus, features only included in the OOFEM implementation, *i.e.* the patch refinement and stress recovery techniques, should be implemented also in LS-DYNA to fully exploit the adaptive method. Since the stress recovery technique in **Paper B**

[1] Currently, LS-DYNA does not allow for the extra nodes to be dynamically allocated during the simulation.

needs access to non-local IP data, this can be cumbersome to implement in a commercial software. Therefore, an element-local stress recovery technique like Extended 2D [46] can be used instead.

The damping procedures, proposed in **Paper C**, can reduce the non-physical oscillations that may occur when refinements are activated in an explicit solver. However, especially the weak refinement damping method is not very versatile and a more refined method that can damp individual nodes should be implemented. Alternatively, the damping can be replaced, *e.g.* by employing some time-bridging technique like the Arlequin method [47, 48]. Then the model can go smoothly from unrefined to refined over a period of time.

For the LS-DYNA implementation (**Papers C-D**), the software-internal calculation of the computational time step does not exploit the fact that the stiffness in the thickness direction for most laminated composites is around an order of magnitude lower than the stiffness in the in-plane directions. This means that the thickness of the element can be considerately smaller than the in-plane length without having the computational time step violate the (true) critical time step. However, refining an element through the thickness can still lead to violation of the critical time step. Thus, the computational time step must be adjusted accordingly, either for the entire model or by utilising a sub-cycling technique. Alternatively, (selective) mass-scaling should be adopted to keep the computational benefit.

Finally, the adaptive modelling method I have presented in this thesis is indeed able to reproduce the same results a high-fidelity model. However, the method can never produce more accurate results than a state-of-the-art high-fidelity model. It can only achieve to produce results at lower computational cost. Therefore, I believe that the adaptive modelling method is a good starting point for enabling computationally efficient analysis of progressive failure in laminated composites. With further developments of the method, crash simulations of full-scale vehicles made of laminated composites can become feasible. I dare to say that achieving this is a prerequisite if structural composites are to have a widespread use in future automotive vehicles.

References

[1] European Commission. *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system.* Tech. rep. 2011, 1–31. DOI: 10.2832/30955.

[2] Chung-Kyu Park, Cing-Dao (Steve) Kan, and William Thomas Hollowell. "Investigation of opportunities for light-weighting a body-on-frame vehicle using advanced plastics and composites". *23rd Enhanced Safety of Vehicles Conference.* Seoul, Korea, 2013.

[3] Johannes Hofer, Erik Wilhelm, and Warren Schenler. Comparing the mass, energy, and cost effects of lightweighting in conventional and electric passenger vehicles. *Journal of Sustainable Development of Energy, Water and Environment Systems* **2**.3 (Sept. 2014), 284–295. DOI: 10.13044/j.sdewes.2014.02.0023.

[4] Ruth Heuss et al. *Lightweight, heavy impact - How carbon fiber and other lightweight materials will develop across industries and specifically in automotive.* Tech. rep. McKinsey & Company, 2012, 1–24.

[5] Henrik Molker. "Failure prediction of orthotropic Non-Crimp Fabric reinforced composite materials". Licentiate thesis. Chalmers University of Technology, Gothenburg, 2016.

[6] Mathilda Karlsson Hagnell. "Technical cost modelling and efficient design of lightweight composites in structural applications". PhD thesis. KTH, 2019. ISBN: 9789178731046.

[7] Per Mårtensson. "Framework for cost and weight efficient conceptual design of automotive composite body structures". PhD thesis. KTH, 2016. ISBN: 9789175959443.

[8] Jean Rouchon. "Certification of large aircraft composite structures, recent progress and new trends in compliance philosophy". *17th ICAS Congr.* Vol. 2. Stockholm, 1990, 1439–1447.

[9] Henrik Molker. "Industrial framework for hot-spot identification and verification in automotive composite structures". PhD thesis. Chalmers University of Technology, 2019. ISBN: 978-91-7597-864-2.

[10] Stephane Mahdi. "Bondline analysis and Bonded Repairs". *CACRC Meeting / Workshop for Composite DT & Maintenance.* Tokyo, 2009.

[11] Renaud Gutkin. *Private Communication.* 2016.

[12] Porsche Media Central. *Porsche 918 Spyder.* 2013. URL: http://press.porsche.com/media/gallery2/v/photos/models/918-Spyder/ (visited on 04/18/2016).

[13] H. Hamada et al. Comparison of energy absorption of carbon/epoxy and carbon/PEEK composite tubes. *Composites* **23**.4 (1992), 245–252. DOI: 10.1016/0010-4361(92)90184-V.

[14] D. Hull. A unified approach to progressive crushing of fibre-reinforced composite tubes. *Composites Science and Technology* **40**.4 (1991), 377–421. DOI: 10.1016/0266-3538(91)90031-J.

[15] Lisa Grauers, Robin Olsson, and Renaud Gutkin. Energy absorption and damage mechanisms in progressive crushing of corrugated NCF laminates: Fractographic

analysis. *Composite Structures* **110** (2014), 110–117. DOI: 10.1016/j.compstruct.2013.11.001.

[16] ERTRAC. *European Roadmap Safe Road Transport.* Tech. rep. European Road Transport Research Advisory Council, 2011.

[17] A.C. Orifici, I. Herszberg, and R.S. Thomson. Review of methodologies for composite material modelling incorporating failure. *Composite Structures* **86**.1-3 (2008), 194–210. DOI: 10.1016/j.compstruct.2008.03.007.

[18] J.N. Reddy. *Mechanics of Laminated Composite Plates: Theory and Analysis.* Boca Raton, CRC Press, 1997. ISBN: 0-8493-3101-3.

[19] Erasmo Carrera. Theories and Finite Elements for Multilayered Plates and Shells:A Unified compact formulation with numerical assessment and benchmarking. *Archives of Computational Methods in Engineering* **10**.3 (2003), 215–296. DOI: 10.1007/BF02736224.

[20] Ireneusz Kreja. A literature review on computational models for laminated composite and sandwich panels. *Open Engineering (formerly Central European Journal of Engineering)* **1**.1 (2011), 59–80. DOI: 10.2478/s13531-011-0005-x.

[21] Paolo Feraboli et al. LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen. *Composites Part A: Applied Science and Manufacturing* **42**.11 (2011), 1809–1825. DOI: 10.1016/j.compositesa.2011.08.004.

[22] Engenuity Limited. *Czone.* URL: http://www.compositesanalysis.com/crash/simulation/ (visited on 12/06/2019).

[23] L. Greve and A.K. Pickett. Delamination testing and modelling for composite crash simulation. *Composites Science and Technology* **66**.6 (2006), 816–826. DOI: 10.1016/j.compscitech.2004.12.042.

[24] Wei Tan, Brian G. Falzon, and Mark Price. Predicting the crushing behaviour of composite material using high-fidelity finite element modelling. *International Journal of Crashworthiness* November (2014), 1–18. DOI: 10.1080/13588265.2014.972122.

[25] C.S. Lopes et al. Physically-Sound Simulation of Low-Velocity Impact on Fibre Reinforced Laminates. *International Journal of Impact Engineering* (June 2015). DOI: 10.1016/j.ijimpeng.2015.05.014.

[26] Matthias Hörmann and Marco Wacker. "Simulation of the crash performance of crash boxes based on advanced thermoplastic composite". *5th European LS-DYNA Users Conference.* 2005.

[27] B.P. Bussadori, K. Schuffenhauer, and A. Scattina. Modelling of CFRP crushing structures in explicit crash analysis. *Composites Part B: Engineering* **60** (2014), 725–735. DOI: 10.1016/j.compositesb.2014.01.020.

[28] Thomas Bru. "Material characterisation for crash modelling of composites". PhD thesis. Chalmers University of Technology, 2018. ISBN: 9789175978055. DOI: 10.13140/RG.2.2.10536.01280.

[29] Sérgio Costa. "Physically based constitutive models for crash of composites". PhD thesis. Chalmers University of Technology, 2019. ISBN: 9789179051549.

[30] Brian G. Falzon. *ICONIC ITN.* URL: https://blog.qub.ac.uk/wordpress/iconic/ (visited on 12/11/2019).

[31] Roland Wohlecker. *MATISSE.* URL: http://www.project-matisse.eu/ (visited on 12/11/2019).

[32] D.J. Mortell, D.A. Tanner, and C.T. McCarthy. In-situ SEM study of transverse cracking and delamination in laminated composite materials. *Composites Science and Technology* **105** (2014), 118–126. DOI: `10.1016/j.compscitech.2014.10.012`.

[33] Kumchol Yun et al. A Damage Model Reflecting the Interaction between Delamination and Intralaminar Crack for Failure Analysis of FRP Laminates. *Applied Sciences* **9**.2 (2019), 314. DOI: `10.3390/app9020314`.

[34] Ted Belytschko and Tom Black. Elastic crack growth in finite elements with minimal remeshing. *International Journal for Numerical Methods in Engineering* **45**.5 (1999), 601–620. DOI: `10.1002/(sici)1097-0207(19990620)45:5<601::aid-nme598>3.0.co;2-s`.

[35] Nicolas Moës, John Dolbow, and Ted Belytschko. A finite element method for crack growth without remeshing. *International Journal for Numerical Methods in Engineering* **46**.1 (1999), 131–150. DOI: `10.1002/(SICI)1097-0207(19990910)46:1<131::AID-NME726>3.0.CO;2-J`.

[36] Daosheng Ling, Qingda Yang, and Brian Cox. An augmented finite element method for modeling arbitrary discontinuities in composite materials. *International Journal of Fracture* **156**.1 (2009), 53–73. DOI: `10.1007/s10704-009-9347-2`.

[37] Anita Hansbo and Peter Hansbo. A finite element method for the simulation of strong and weak discontinuities in solid mechanics. *Computer Methods in Applied Mechanics and Engineering* **193**.33 (2004), 3523–3540. DOI: `10.1016/j.cma.2003.12.041`.

[38] Mark McElroy. "An enriched shell element for delamination simulation in composite laminates". *American Society for Composites 30th Technical Conference*. East Lansing, 2015.

[39] Saman Hosseini, Joris J.C. Remmers, and Clemens V. Verhoosel. Propagation of delamination in composite materials with isogeometric continuum shell elements. *International Journal for Numerical Methods in Engineering* **102** (2014), 159–179. DOI: `10.1002/nme`.

[40] Roland Wohlecker. *Modelling And Testing for Improved Safety of key composite StructurEs in alternatively powered vehicles - Summary of implemented composite modelling methods and outcome of their validation*. Tech. rep. 2015.

[41] Jim Brouzoulis and Martin Fagerström. An enriched shell element formulation for efficient modeling of multiple delamination propagation in laminates. *Composite Structures* **126** (2015), 196–206. DOI: `10.1016/j.compstruct.2015.02.055`.

[42] Jim Brouzoulis, Martin Fagerström, and Erik Svenning. An enriched shell element formulation for modeling of inter- and intralaminar crack propagation in laminates. *Composite Structures* **136** (2015), 616–625. DOI: `10.1016/j.compstruct.2015.10.028`.

[43] Borek Patzák. *OOFEM*. 2000. URL: `www.oofem.org` (visited on 04/25/2017).

[44] Roland Wohlecker. *Modelling And Testing for Improved Safety of key composite StructurEs in alternatively powered vehicles - Implementation of an XFEM composite element into LS-DYNA*. Tech. rep. 2015.

[45] Thomas Menouillard and Ted Belytschko. Smoothed nodal forces for improved dynamic crack propagation modeling in XFEM. *International Journal for Numerical Methods in Engineering* **84**.1 (2010), 47–72. DOI: `10.1002/nme.2882`.

[46] Philipp G Nolden, Raimund Rolfes, and Guido Kuhlmann. "Efficient Transverse Stress Calculation and Failure Prediction in Arbitrarily Curved Shell-Structures Using TRAVEST". *Proceedings of the MSC.Software 2002 Worldwide Aerospace Conference and Technology Showcase*. Toulouse, France, 2002.

[47] Hashmi Ben Dhia and Guillaume Rateau. The Arlequin method as a flexible engineering design tool. *International Journal for Numerical Methods in Engineering* **62**.11 (2005), 1442–1462. DOI: 10.1002/nme.1229.

[48] S. P. Xiao and T. Belytschko. A bridging domain method for coupling continua with molecular dynamics. *Computer Methods in Applied Mechanics and Engineering* **193**.17-20 (May 2004), 1645–1669. DOI: 10.1016/j.cma.2003.12.053.

Part II
Appended Papers A–D